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The Collapse of Interstellar and Intergalactic Gas Clouds

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1. Introduction.

This contract set out basically to cover the costs of

(a) 2 research students

(b) 1 graduate assistant

(c) 1 Friden Teleprinter and tape editing set.

The contract supported the 2 research students for a period of two academic years. Support for the final year of their Ph.D. studies came from Perren Funds of the University of London. The graduate assistant was supported for one year on the funds of the contract but was subsequently supported by University College London as a departmental assistant.

The Teleprinter was used to prepare paper tape input for the University of London Atlas Computer. Since the successful outcome of this work centered on ready access to a large computer the teleprinter was vital to this project and the costs of rental of the teleprinter were borne entirely by the contract. The rental of the teleprinter will be taken over by the department at the termination of the contract.

Other funds in the contract provided for travelling expenses to conferences within the range of interest covered by contract.

The personnel associated with the problem covered by the contract were:-

(i) Dr. D. McNally - Principal Investigator 1964-68

(ii) Mr. M.J. Disney - Research Student 1965-1968 (awarded Ph.D. degree 1968)

(iii) Mr. R.C. Gamble - Research Assistant 1965-1968 (registered for M.Phil. degree)

(iv) Mr. A.E. Wright - Research Student 1965-1968 (awarded Ph.D. degree 1968)

Dr. M.J. Disney is now at the Steward Observatory of the University of Arizona, Dr. A.E. Wright is with the Hatfield Polytechnic (formerly the Hatfield College of Technology) developing new astronomical studies, while Mr. R.C. Gamble remains at the University of London Observatory.

2. Nature of the Star Formation Problem.

The problem covered by this contract was that of star formation through the collapse of interstellar gas clouds under their own self-gravitation. This is not a new idea in the field of star formation as the idea can be traced back at least as far as Laplace. However, the problem had only been considered for simplified conditions which were unrealistic and which probably in no small measure contributed to two of the major difficulties (fragmentation and angular momentum) encountered by the theory. The aim of the present work was to apply numerical methods to the problem to find out if the ability to take account of more complex situations could alter the situation.

2.1. Jeans' Criterion.

Most of the recent work on star formation is intimately connected with the discovery by Jeans (in 1905) of the initial mass likely to collapse under its own self gravitation. This criterion (or the Virial Theorem which later superseded it) can be extended to take into account effects of cloud rotation and magnetism as well as mass motion, pressure and gravitation. However, most of the work based on the Jeans' criterion is concerned with gas clouds of almost uniform density.

The Jeans' Criterion simply states that a gas cloud of fixed mean density and mean kinetic temperature cannot collapse under its own self gravitation unless its radius is larger than a certain critical value. Addition of angular momentum and magnetism increases the size of critical radius. While it was recognised early that efficient cooling was necessary to maintain a collapse once started no attempts to include cooling processes in a collapse calculation had been made. An unfortunate consequence of the Jeans' Criterion was that in order to obtain collapse with what were thought to be reasonable values of interstellar density and temperature a very massive gas cloud. ($\sim 10^{[illegible]}-10^{[illegible]}$ solar masses) was required. The problem of obtaining an object of one solar mass proved difficult to solve. Clearly as the gas cloud increased in density and cooled the Jeans' Criterion would apply to sub-regions of the gas cloud. However, such subregions could not collapse substantially faster than the parent gas cloud unless they were initially substantially denser. This led to a circuitous argument that in order to have fragmentation the gas cloud had to be fragmented initially.

Theories based on the growth of infinitesimal perturbations have been proposed. However, the theory of the growth of perturbations are based on the assumption of zero gas pressure. It is not clear how the growth of perturbations would be affected by even a small amount of residual gas pressure. Under these circumstances the problem of cloud fragmentation into small collapsing masses is difficult to envisage.

3. The nature of the interstellar gas problem.

A second problem investigated during the tenure of this contract was the preparation of a detailed catalogue of interstellar line intensities both for the identified atomic and molecular species and for the unidentified diffuse features. The bulk of the information on interstellar lines comes as a by-product of work done for purposes other than interstellar and consequently the information comes presented in many different formats. Fortunately there are a few surveys of interstellar line intensities which permit the setting up of a standard system.

It became apparent early in the work that the available information was ill distributed in the sense that some lines (e.g. the diffuse feature at $\lambda 4430$ A^{o}, the H and K lines of Ca^{+}) were well observed while the great majority were observed in very few stars and in some cases had been observed only once in the spectrum of a single star. It also became apparent during the survey that much more information on interstellar lines lay unreduced and unpublished.

The aim of producing a catalogue of this type is to assemble a large amount of fairly consistent data which may later by analysed to give new information about the interstellar gas. Unfortunately in view of the sporadic nature of interstellar work many samples will not be statistically significant. However, the catalogue should go some way to minimise this situation.

4. A theory of star formation.

In order to develop a theory of star formation based on collapse under gravity which differed appreciably from its predecessors, it was necessary to investigate the collapse problem in considerable detail. It was not possible to approach the problem analytically except under specialised circumstances. It was therefore decided that only a numerical approach would give results of any value.

4.1. Numerical Methods.

At the time that this work was started (1962) there were no satisfactory methods for dealing with the numerical integration of the equations of hydrodynamics with gravitation. Since that time methods have been developed most notably in the theory of pulsating stars. However, such methods were usually in a Lagrangian formulation of the equations which we have been unwilling to adopt in view of the fact that magnetic and angular momentum problems can only be treated in Eulerian form. Therefore this work is almost unique in developing numerical methods for the equations of hydrodynamics with gravitation in Eulerian form.

It was found that a finite difference approximation to such equations could be satisfactory provided:

(a) space derivatives were calculated with sufficient accuracy - usually by 4 or 6 point formulae,

(b) adequate distinction was drawn between motion of the physical gas and motion of the coordinates mesh (through the addition of extra terms to the equations),

(c) an iterative proceedure was used to advance in time (direct advances in time were unstable),

(d) the calculation was not extended as a single stage beyond a free fall time determined by the initial central density of the gas cloud.

The adequacy of the numerical solutions were checked for internal consistency by:

(a) variation of the length of space and time steps

(b) intercomparison of the different finite difference schemes

(c) comparison with certain analytic solutions (linear wave flow) of the non-linear problem.

The accuracy of the solution was found to be good using all these methods and interagreement of better than 10 per cent was obtained. It was found that integral tests which had commonly been used with these methods over-estimated accuracy unless interpreted very carefully.

These simple numerical proceedures were found too unreliable after the elapse of a free fall time determined by the initial central density. Calculations could not be taken beyond this point. Two lines of enquiry were then open. Either a new numerical method had to be found or analytical methods might be used as guides. For the purpose of this report the second method was used. Therefore the later stages of our star formation theory become qualitative rather than quantitative. Various numerical devices were of course tried but most were found to be of the nature of palliatives rather than solutions in view of the fact that at the free fall time a physical "singularity" ought to appear. However, a new method of numerical approach did ultimately appear. As this is in the course of investigation to determine its value it will not be discussed further in this report except to say that the methods offer hope of a way in which the "singularity" may be avoided.

4.2. The theory of star formation.

The collapse of gas clouds of all types followed a similar pattern. Cooling through the excitation of C^+, Si^+, Fe^+, Mg^+ was considered. At the start of this work it was the dominant cooling process though a recently discovered cooling process dependant on atomic oxygen has changed this situation the difference is not significantly different in the temperature range $0 \leq T \leq 1000^{\circ}K$. It is this temperature range which is of relevance in this work.

Because of the character of the cooling processes the early place of collapse - Phase I - is cooling dominated. Initial temperatures in excess of 10°K are reduced to this value and the central regions of the gas cloud become isothermal. A linear wave velocity field is set up near the cloud centre. During this phase the initial density distribution of the gas cloud is hardly altered.

Heating of the cloud has little effect on the behaviour of the central part of the gas cloud. Heating by cosmic rays (for example) will only affect the motion of the outer part of the gas cloud by setting up an expansion in the outer region of the gas cloud. The expansion is usually negligible in massive (10^{39}gm) gas clouds and is often later reversed but can build up substantially in small gas clouds (10^{35}gm).

The rate at which collapse proceeds is determined by reduction in pressure gradient relative to the gravitational force. Clearly the more nearly free fall conditions are approached the faster central condensation can take place. In all the models considered the pressure forces were quickly reduced to less than 10 per cent of the gravitational forces at the centre of the gas cloud. As the outer boundary of the gas cloud was reached the initial values of density and temperature were less disturbed as the cooling rate falls rapidly as density and temperature tend to zero. We now have a situation which gives a rudimentary form of fragmentation through dependence of the cooling rate on density and temperature distribution. This form is hidden if homologous collapse of a uniform gas cloud is considered as has been usual hitherto.

After Phase I has ended, Phase II begins - a stage in which central condensation builds up while the cooling maintains almost isothermal conditions by being adequate to remove any compressional heating. During Phase II the central density builds up isothermally. Towards the end of this phase the central temperature begins to rise slowly.

Phase II is of considerable interest in other respects. It was found that during Phase II perturbations grew. Large perturbation of density grew at a rate comparable with that of the central condensation so that under such circumstances the original cloud could be envisaged as breaking into several subclouds each collapsing on its own. The growth of small density perturbations was particularly interesting. It was found that particular conditions of growth were necessary. For example a perturbation near the outside of the cloud smoothed out and did not grow while a perturbation near the cloud centre grew and usually gave an indication that several density maxima could result from the initial perturbation (the number of density maxima has not yet been worked out in detail). It became clear from the numerical studies that the conditions of perturbation growth could be more readily established than by analytical procedures in limiting cases. Perturbations will only grow provided the conditions of force field and velocity gradient are correct. The force field had to increase outwards in association with a negative velocity gradient (remembering that the velocity is negative i.e. directed towards the centre). If the velocity gradient were positive and the force field decreased outwards then no growth of perturbations could be obtained. The size of the region of the gas cloud that could be affected by perturbations was therefore determined by the position of the maximum inward velocity which was in turn affected by the density distribution. The maximum of inward velocity moved towards the boundary as the density distribution became flatter. In general one can say that perturbation could be effective out to 0.6R where R is the radius of the cloud.

Phase II is ended when the gas cloud becomes opaque to the cooling radiation. Phase III of the collapse concerns the first opaque phase of collapse. Once the cloud becomes opaque the gas cloud no longer cools so that the temperature begins to rise again in the central part of the gas cloud. However, there is no danger at first of a halt to the collapse since gravity controls the motion in the central regions of the cloud. In Phase III the numerical calculation breaks down irrepairably. Again, this is not as disastrous as it might seem at first sight. Since the gas cloud is not losing energy one may suppose that the cloud is adiabatic. Since the central regions are collapsing in linear wave flow we can use the appropriate analytical solutions for adiabatic linear wave flow.(The checking of numerical solutions against the analytical linear wave solutions provided considerable incentive to investigate these flows. As a result many solutions are known and are of the very greatest value in extending and interpreting the numerical work). Using an adiabatic linear wave flow model the calculation can be carried further forward in time.

The onset of the opaque phase takes place progressively. Clearly opacity depends on the depth of material involved and the central regions of the cloud will not suffer from the effects of opacity even though the cloud as a whole has become opaque. This means that the central parts of the gas cloud are not quite adiabatic but continue to lose energy and so maintain the collapse. The central peak of the density distribution continues to grow and becomes even more separated from the main body of the gas cloud. Again fragmentation is assisted. Eventually opacity is found over all reasonable distance scales and the model becomes wholly adiabatic. Phase III terminates when the temperature in the central region becomes about 10^4 °K.

Phase IV begins when the hydrogen begins to ionise at about 10^4 °K. Cooling again takes place in the centre of the cloud through free-free and free-bound transitions of hydrogen and through the ionisation of hydrogen. Indeed the ionisation of hydrogen is able to maintain the temperature at about 10^4 °K. In consequence a new collapse is started in Phase IV. This phase is similar to Phase II and the results for Phase II can be used in Phase IV. Eventually "atomic hydrogen cooling" (in the above sense) becomes inadequate and the final Phase (V) similar to Phase III is entered. During this phase stellar densities and temperatures appropriate to nuclear reactions are encountered. Phase V is short - of the order of several days and it is in this phase that neglect of a proper treatment of radiative transfer, rotational and magnetic forces is most apparent. A star in Phase V would "crash" in to the main sequence rather than "arrive" on it. The main details of each Phase are summarised in the table below.

Summary of the proposed Star Formation Theory

Phase	Density ($9cm^{-3}$)	Temperature (°K)	Timescale (S)	Timescale (Yr)
I	10^{-23}	initial→10	2.10^{13}	7.10^{5}
II	$10^{-23}\rightarrow 10^{-13}$	10	5.10^{14}	2.10^{7}
III	$10^{-13}\rightarrow 10^{-8.5}$	$10\rightarrow 10^{4}$	5.10^{9}	2.10^{2}
IV	$10^{-8.5}\rightarrow 10^{-4}$	10^{4}	3.10^{7}	1
V	$10^{-4}\rightarrow 1$	$10^{4}\rightarrow 4.10^{6}$	2.10^{5}	.007

Several interesting details emerge from this work. At a temperature of 10 °K and a density of 10^{-23} 9 cm the smallest mass capable of collapsing under its own self gravitation is $10^{-35.5}$ gm. which is about the mass of a galactic cluster.

In order to reach stage IV the central condensation has to have a mass of 10^{32} gm which is about the minimum stellar mass.

The numerical methods which we have developed so far have enabled us to justify the evolution as far as the changeover from Phase II to Phase III. We have not been able to follow the evolution as far as a density of $10^{-13} g\ cm^{-3}$ since this depends on an analysis of opacity but our calculations have proceeded sufficiently far to make the extrapolation plausible. The behaviour in Phase III is derived from an adiabatic model and Phase IV may be compared with Phase II. Phase V is again based on the adiabatic model. At present the precise details of the changes between Phases II and III, III and IV, and IV and V are not established though the behaviour in each Phase is well established. It is hoped that the new numerical techniques now under consideration will complete the understanding of some of these transitions. However, it is felt that the present evidence supports the above view.

4.3. Interstellar Line Catalogue.

The catalogue of interstellar line equivalent widths is now complete. The data extracted from the literature was placed on a single scale using empirical relations between values of different surveys (provided an overlap of twenty or more stars existed between surveys). If no overlap existed the results of the survey were documented but the weighting system prevents the use of these results in any statistical analysis. Many surveys gave only measurements of central intensity. Again an empirical result could be established to relate central intensity and equivalent width. The equivalent widths obtained in this way have a lower significance than direct measurements.

The data is maintained as a card file which may be readily updated and it is planned to place the file on an IBM 1130 type magnetic disc for ease of handling. The file contains not only information on interstellar features on a star by star basis but also contains details of stellar characteristics and other data of relevance to the interstellar problem. Coordination analysis is thereby facilitated.

In order to check the usefulness of the data three pilot experiments were tried:-

(a) It is normally assumed that the interstellar absorption takes place in space and that the interstellar gas is transparent. This last assumption means that the source of background illumination (the star in whose spectrum the interstellar line appears) should not affect the equivalent width of the absorption line.

In fact a strong correlation with stellar luminosity class was found. However, in the experiment distance efforts were not removed but there is a strong indication that the effect would persist even though distance effects were removed. All interstellar features which had measurements of equivalent width behaved in a similar fashion.

(b) An attempt was made to see if contours of equal equivalent width could be constructed on the sky. Using a sophisticated proceedure it was found that such contours could be drawn. However, it has not yet proved possible to check the reality of such contours.

(c) An attempt was made to investigate a prediction made by McNally and Somerville that a certain structure existed in the diffuse interstellar features. The prediction was not well confirmed in view of the paucity of observation in some cases. However, surprising correlations were found in that lines in one structure group correlated better with lines of a different structure group.

These initial experiments demonstrated the usefulness of the file and while giving somewhat conflicting results (in that the results of (a) and (b) could be argued to be at variance) show that it will be possible through more critical analysis to obtain useful new results. Such studies are now in progress.

4. Publications.

4.1 Theses.

Two theses have been submitted to the University of London to satisfy the requirements of the Ph.D. degree. Both theses were examined and found to be acceptable. The external examiners of both theses commended them highly. The theses were:

M.J. Disney; Numerical Studies of Collapse Processes in Cosmical Gas Clouds. August 1968.

A.E. Wright; On the Problems of Interstellar Gravito-Gas Dynamics. June 1968.

A further M.Phil. theses on the Interstellar Line Catalogue is in the course of preparation.

4.2. Papers.

The following papers have been published:

1. Numerical Methods in Gravitational Collapse Problems.
   Mem.R.Soc., Leige. 41,301,1966. D. McNally.

2. Properties of the Interstellar Medium.
   Mem.R.Soc., Leige. 41,279,1966. D. McNally.

3. Fragmentation and Angular Momentum - are they real problems in theories of star formation?
   Mem.R.Soc., Leige. 41,329,1966. D. McNally.

4. Interstellar Molecules.
   Adv. Astro. Astrophys. 6,173,1968 D. McNally.

5. The Collapse of Interstellar Gas Clouds, II. An analytical study.
   Mon.Not.R.astr.Soc. 140,319,1968. M.J.Disney, D.McNally A.E.Wright.

The following papers are in preparation:

6. The Collapse of Interstellar Gas Clouds, III. Numerical Methods.
   D.J.Crampin, M.J.Disney, D.McNally, A.E.Wright.

7. The Collapse of Interstellar Gas Clouds, IV. A theory of star formation.
   M.J. Disney, D.McNally, A.E. Wright.

8. Structure among the Interstellar Diffuse Features.
   D.McNally, W.B. Somerville.

It is hoped to submit 6 and 7 to the Royal Astronomical Society (Mon.Not.) and 8 to The Observatory. In addition it is proposed to publish tables of model gas cloud evolution as a Publication of the University of London Observatory.

5. Acknowledgement.

Without the support of the ONR Contract this work could not have been carried to the present stage of a plausible theory of star formation. It is a particular pleasure to record our gratitude for this Contract and the happy and cordial relations with ONR during the period of its validity.